

False-name-proof Mechanisms for Hiring a Team<sup>☆</sup>Atsushi Iwasaki<sup>\*,a</sup>, David Kempe<sup>b</sup>, Mahyar Salek<sup>b</sup>, Makoto Yokoo<sup>a</sup><sup>a</sup>*Graduate School of ISEE, Kyushu University, Fukuoka 819-0395, Japan*<sup>b</sup>*Department of Computer Science, University of Southern California, CA 90089-0781, USA*

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**Abstract**

We study the problem of hiring a team of selfish agents to perform a task. Each agent is assumed to own one or more elements of a set system, and the auctioneer is trying to purchase a feasible solution by conducting an auction. Our goal is to design auctions that are truthful and false-name-proof, meaning that it is in the agents' best interest to reveal ownership of all elements (which may not be known to the auctioneer a priori) as well as their true incurred costs.

We first propose and analyze a false-name-proof mechanism for the special case where each agent owns only one element in reality, but may pretend that this element is in fact a set of multiple elements. We prove that its frugality ratio is bounded by  $2^n$ , which, up to constants, matches a lower bound of  $\Omega(2^n)$  for all false-name-proof mechanisms in this scenario. We then propose a second mechanism for the general case in which agents may own multiple elements. It requires the auctioneer to choose a reserve cost a priori, and thus does not always purchase a solution. In return, it is false-name-proof even when agents own multiple elements. We experimentally evaluate the payment (as well as social surplus) of the second mechanism through simulation.

*Key words:* mechanism design, hiring a team, truthfulness, false-name-proofness

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## 1. Introduction

One of the important challenges of electronic commerce, in particular in large-scale settings such as the Internet, is to design protocols for dealing with parties having diverse and selfish interests. Frequently, one of the most convenient ways of structuring these interactions is via *auctions*: based on bids submitted by the participants, the auctioneer chooses whom to sell items to or purchase items from, and decides on appropriate payments. The analytical study of auctions for e-commerce has recently led to very fruitful interactions between the fields of economics, game theory, theoretical computer science, and artificial intelligence.

While single-item auctions have a long history of study in economics (see, e.g., [1, 2]), the problem is significantly more complex when there are combinatorial dependencies between items. In a *combinatorial auction* [3], the auctioneer has a set of items for sale, and agents submit bids for different subsets. Each item can only be assigned to one agent.

In contrast to combinatorial auctions, where an auctioneer is trying to *sell* a set of items, we study the problem of *hiring a team of agents* [4, 5, 6]. In that problem, an auctioneer knows which subsets of agents can perform a complex task together, and needs to hire such a team. (called a *feasible set* of agents.) Since the auctioneer does not know the true costs incurred by agents, we assume that the auctioneer will use an auction to elicit bids. A particularly well-studied special case of this problem is that of a *path auction* [4, 7, 8, 9]: the agents own edges of a known graph, and the auctioneer wants to purchase an *s-t* path.

Selfish agents will try to maximize their profit, even if it requires misrepresenting their incurred cost or their identity. The field of *mechanism design* focuses on the design of the interaction between agents and computation to mitigate the effects of such selfish behavior [9, 10, 11]. In particular, there has been a lot of recent focus on the design of *truthful* auctions, in which it is in the agents' best interest to reveal their true costs to the auctioneer.

While the concept of truthfulness addresses the concern that agents may misrepresent their true costs, there is a second way in which agents could cheat: an agent owning multiple elements of a set system (such as multiple edges in a graph) may choose different identities for interacting with the auctioneer, to obtain higher payments. Similarly, an agent owning one element may be able to pretend that this element is in fact a set of multiple elements, owned by different agents, to obtain payments for all of these

“pseudo-agents”. Such behavior is called *false-name manipulation*, and was recently studied by Yokoo et al. in the context of combinatorial auctions [12, 13], where it was shown that for any Pareto efficient auction, agents can profit by submitting bids as two identities.

### 1.1. Our contributions

We introduce a model of false-name manipulation in auctions for hiring a team, such as  $s$ - $t$  path auctions. In this model, the set system structure and element ownership are not completely known to the auctioneer. Thus, in order to increase profit, an agent who owns an element can pretend that the element is in fact a set consisting of multiple elements owned by different agents. Similarly, an agent owning multiple elements can submit bids for these elements under different identities. We call a mechanism *false-name-proof* if it is truthful, and a dominant strategy is for each agent to reveal ownership of all elements.

Our first main contribution is a false-name-proof mechanism MP for the special case in which each agent owns exactly one element. Thus, the mechanism only needs to guard against an agent pretending that a single element is a set of elements, owned by distinct agents. This mechanism introduces an exponential multiplicative penalty against sets in the number of participating agents. We show that its frugality ratio (according to the definition of Karlin et al. [8]) is at most  $2^n$  for all set systems of  $n$  elements, which matches — up to constants — a worst-case lower bound of  $\Omega(2^n)$  we establish for *every* false-name-proof mechanism.

When agents may own multiple elements, designing either a false-name proof mechanism with bounded frugality ratio or proving an impossibility result appears challenging. The main reason is that we currently do not have a good characterization of incentive-compatible mechanisms with a sufficiently complex action space for the agents. Instead, we present an alternative mechanism AP, based on an a priori chosen reserve cost  $r$  and additive penalties. The mechanism is false-name-proof in the general setting, but depends crucially on the choice of  $r$ , as it will not purchase a solution unless there is one whose cost (including the penalty) is at most  $r$ . We investigate the AP mechanism experimentally for  $s$ - $t$  path auctions on random graphs, observing that AP provides social surplus not too far from a Pareto efficient one at an appropriate reserve cost. Also, the payments of AP are smaller than those of the Vickrey-Clarke-Groves (VCG) mechanism when the reserve cost

is small, while they become higher than VCG's when the reserve cost is high. However, the payment never exceeds the reserve cost.

### 1.2. Related Work

Motivated by the need to deal with selfish users, there has been a large body of recent work at the intersection of game theory, economic theory and theoretical computer science (see, e.g., [14, 11]). For instance, the seminal paper of Nisan and Ronen [9], which introduced mechanism design to the theoretical computer science community, studied the tradeoffs between agents' incentives and computational complexity. The loss of efficiency in network games due to selfish user behavior has been studied under the names of "price of anarchy" (see, e.g., [11, 15]), and "price of stability" (see [16]).

The problem of hiring a team of agents in complex settings, at minimum total cost, has been shown to have many practical economic applications (see [17, 18, 19, 20] for examples). In particular, the path auction problem has been the subject of a significant amount of prior research. The traditional economics approach to payment minimization (or profit maximization) is to construct the optimal Bayesian auction given the prior distributions from which agents' private values are drawn. Indeed, path auctions and similar problems have been studied recently from the Bayesian perspective in [7, 21]. Here, we instead follow the approach pioneered by Archer, Tardos, Talwar and others [4, 22, 8, 6], and study the problem from a worst-case perspective. Significant insight can be gained from an understanding of worst-case performance, and it enables an uninformed or only partially informed auctioneer to evaluate the trade-off between an auction tailored to assumptions about bidder valuations (which may or may not be correct) versus an auction designed to work as well as possible under unknown and worst-case market conditions.

If false-name bids are not a concern, then it has long been known that the VCG mechanism [23, 24, 25] gives a truthful mechanism and identifies the Pareto optimal solution. It is based on Vickrey's second-price auction [23], which is truthful for single-item auctions. As the payments of VCG can be significantly higher than the cheapest alternative solution, several papers [4, 6, 7, 8] have investigated the *frugality* of mechanisms: the overpayment compared to a natural lower bound. In particular, Karlin et al. [8] present a mechanism — called the  $\sqrt{\cdot}$  mechanism — achieving a frugality ratio within a constant factor of optimal for  $s$ - $t$  path auctions in graphs. Traditionally,

for “hiring a team” auctions, *incentive compatibility* has only encompassed making the revelation of true *costs* a dominant strategy for each bidder.

The issue of false-name bids has been previously studied in several cases of combinatorial auctions and procurement auctions by Yokoo et al. [26, 27, 28, 29, 12], who developed false-name-proof mechanisms in those scenarios, but also proved that no mechanism can be both false-name-proof and Pareto efficient. Notice that the false-name-proof mechanisms for combinatorial procurement auctions given in [27, 28] cannot be applied in our setting, as they assume additive valuations on the part of the auctioneer, i.e., that the auctioneer derives partial utility from partial solutions. A somewhat similar scenario arises in job scheduling, where users may split or merge jobs to obtain earlier assignments. Moulin [30] gives a mechanism that is truthful/strategy-proof against both merges and splits and achieves efficiency within a constant factor of optimum. However, when agents can exchange money, no such mechanism is possible [30].

For the specific case of path auctions, the impact of false-name bids was studied by Du et al. [31]. They showed that if agents can own multiple edges, then there is no false-name-proof and efficient mechanism. Furthermore, if bids are anonymous, i.e., agents do not report any identity for edge ownership, then no mechanism can be truthful/strategy-proof. Notice that this does not preclude false-name-proof and truthful mechanisms in which the auctioneer takes ownership of multiple edge by the same agent into account, and rewards the agent accordingly.

## 2. Preliminaries

We begin by defining formally the framework for auctions to hire a team. Our framework is based on that of [4, 22, 8, 6]. A *set system*  $(E, \mathcal{F})$  is specified by a set  $E$  of  $n$  *elements* and a collection  $\mathcal{F} \subseteq 2^E$  of *feasible sets*. For instance, in the important special case of an  $s$ - $t$  path auction,  $S \in \mathcal{F}$  if and only if  $S$  is an  $s$ - $t$  path. We are only interested in set systems that are *monopoly-free*, in the sense that  $\bigcap_{S \in \mathcal{F}} S = \emptyset$ , i.e., no agent is in all feasible sets.

In previous work on “hiring a team” auctions, each element  $e$  was associated with a different selfish agent. Here, we depart from this assumption, in that an agent may own *multiple* elements.  $A^i$  denotes the set of elements owned by agent  $i$ , which is an element of a partition  $\mathcal{A}$  of  $E$ . An *owned set system*, i.e., a set system with ownership structure, is specified by  $((E, \mathcal{F}), \mathcal{A})$ .

We use  $o(e)$  to denote the owner of element  $e$ , i.e., the unique  $i$  such that  $e \in A^i$ . Each element  $e$  has an associated *cost*  $c_e$ , the true cost that its owner  $o(e)$  will incur if  $e$  is selected by the mechanism.<sup>1</sup> This cost is *private*, i.e., known only to  $o(e)$ . An *auction* consists of two steps:

1. Each agent  $i$  submits sealed bids  $(b_e, \tilde{o}(e))$  for elements  $e$ , where  $\tilde{o}(e)$  denotes the identifier of  $e$ 's purported owner which need not be the actual owner. (However, no agent  $i$  can claim ownership of an element  $e$  owned by another agent  $i' \neq i$ .)
2. Based on the bids, the auctioneer uses an algorithm that is common knowledge among the agents in order to select a feasible set  $S^* \in \mathcal{F}$  as the winner and compute a payment  $p_i$  for each agent  $i$  with an element  $e$  such that  $i = \tilde{o}(e)$ . We say that the elements  $e \in S^*$  *win*, and all other elements *lose*.

The *profit* of an agent  $i$  is the sum of all payments she receives, minus the incurred cost  $c(S^* \cap A^i)$ . Each agent is only interested in maximizing her profit, and might choose to misrepresent ownership or costs to this end. However, we assume that agents do not collude. Past work on incentive compatible mechanisms has focused on *truthful* mechanisms. That is, the assumption was that each agent  $i$  submits bids only for elements  $e \in A^i$  she actually owns, and reports correct ownership  $o(e) = i$  for all of them. If agents report correct ownership for all  $e \in A^i$ , then a mechanism is truthful by definition if for any fixed vector  $b^{-i}$  of bids by all agents other than  $i$ , it is in agent  $i$ 's best interest to bid  $b_e = c_e$  for all  $e \in A^i$ , i.e., agent  $i$ 's profit is maximized by bidding  $b_e = c_e$  for all these elements  $e$ .

In this paper, we extend the study of truthful mechanisms to take into account *false-name manipulation*: agents claiming ownership of non-existent elements (which we call *self-division*) or choosing not to disclose ownership of elements (which we call *identifier splitting*). Identifier Splitting is the most natural form of false-name bidding on the part of an agent, and the one studied in the past for combinatorial auctions, by Yokoo et al. [12, 13]. The notion of self-division is motivated by graph-theoretic problems (such as shortest paths), when there is uncertainty on the part of the auctioneer about the underlying set system.

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<sup>1</sup>For costs, bids, etc., we extend the notation by writing  $c(S) = \sum_{e \in S} c_e$ ,  $b(S) = \sum_{e \in S} b_e$ , etc.

**Definition 1 (Identifier Splitting [12, 13]).** *An agent  $i$  owning a set  $A^i$  may choose to use different identifiers in her bid for some or all of the elements. Formally, the owned set system  $((E, \mathcal{F}), \mathcal{A})$  is replaced by  $((E, \mathcal{F}), \mathcal{A}')$ , where  $A' = A \setminus \{A^i\} \cup \{A^{i'}\} \cup \{A^{i''}\}$ , and  $A^i = A^{i'} \cup A^{i''}$  when agent  $i$  uses two identifiers  $i'$  and  $i''$ .*

**Definition 2 (Self-Division).** *An agent  $i$  owning element  $e$  is said to self-divide  $e$  if  $e$  is replaced by two or more elements  $e_1, \dots, e_k$ , and different owners are reported for the  $e_i$ . Formally, the owned set system  $((E, \mathcal{F}), \mathcal{A})$  is replaced by  $((E', \mathcal{F}'), \mathcal{A}')$ , whose elements are  $E' = E \setminus \{e\} \cup \{e_1, \dots, e_k\}$ , such that the feasible sets  $\mathcal{F}'$  are exactly those sets  $S$  not containing  $e$ , as well as sets  $S \setminus \{e\} \cup \{e_1, \dots, e_k\}$  for all feasible sets  $S \in \mathcal{F}$  containing  $e$ . The ownership structure is  $A^{i_j} = \{e_j\}$  for  $j = 1, \dots, k$ , where each  $i_j$  is a new agent.*

Intuitively, self-division allows an agent to pretend that multiple distinct agents are involved in doing the work of element  $e$ , and that each of them must be paid separately. For self-division to be a threat, there must be uncertainty on the part of the auctioneer about the true set system  $(E, \mathcal{F})$ . In particular, it is meaningless to talk about a mechanism for an individual set system, as the auctioneer does not know a priori what the set system is. Hence, we define *classes of set systems closed under subdivision*, as the candidate classes on which mechanisms must operate.

- Definition 3.**
1. *For two set systems  $(E, \mathcal{F})$  and  $(E', \mathcal{F}')$ , we say  $(E', \mathcal{F}')$  is reachable from  $(E, \mathcal{F})$  by subdivisions if  $(E', \mathcal{F}')$  is obtained by (repeatedly) replacing individual elements  $e \in E$  with  $\{e_1, \dots, e_k\}$ , such that the feasible sets  $\mathcal{F}'$  are exactly those sets  $S$  not containing  $e$ , as well as sets  $S \setminus \{e\} \cup \{e_1, \dots, e_k\}$  for all feasible sets  $S \in \mathcal{F}$  containing  $e$ .*
  2. *A class  $\mathcal{C}$  of set systems is closed under subdivisions iff with  $(E, \mathcal{F})$ , all set systems reachable from  $(E, \mathcal{F})$  by subdivisions are also in  $\mathcal{C}$ .*

For example,  $s$ - $t$  path auction set systems are closed under subdivisions, whereas minimum spanning tree set systems are not (because subdivisions would introduce new nodes that must be spanned). On the other hand, minimum Steiner tree set systems with a fixed set of terminals are susceptible to false-name manipulation.

In both identifier splitting and self-division, we will sometimes refer to the new agents  $i'$  whose existence  $i$  invents as *pseudo-agents*. A mechanism is *false-name-proof* if it is a dominant strategy for each agent  $i$  to simply report the pair  $(c_e, i)$  as a bid for each element  $e \in A^i$ . Thus, neither identifier splitting nor self-division nor bids  $b_e \neq c_e$  can increase the agent's profit. Among other things, this allows us to use  $b_e$  and  $c_e$  interchangeably when discussing false-name-proof mechanisms. Notice that we explicitly define the concept of false-name-proof mechanisms to imply that the mechanism is also truthful when each agent  $i$  owns only one element.

### 2.1. Efficiency and Frugality

In designing and analyzing a mechanism for hiring a team, there are several other desirable properties besides being false-name-proof (or at least truthful). Two particularly important ones are efficiency and frugality. A mechanism is *Pareto efficient* if it always maximizes the sum of all participants' utilities (including that of the auctioneer). This maximizes social surplus. In the case of hiring a team, the auctioneer's utility is exactly  $-\sum_i p_i$ , the negative of the sum of all payments. Hence, all payments cancel out, and a mechanism is Pareto efficient if and only if it always purchases the cheapest team or  $s$ - $t$  path. While it is well-known that the VCG mechanism is truthful and Pareto efficient [23, 24, 25], Du et al. [31] show that there is no Pareto efficient and false-name-proof mechanism, even for  $s$ - $t$  path auctions. Yokoo et al. [13] showed the same for combinatorial auctions.

While Pareto efficient mechanisms maximize social welfare, they can significantly overpay compared to other mechanisms [8, 7]. In order to analyze the overpayment, we use the definition of *frugality ratio* from [8]. The idea of the frugality ratio is to compare the payments to a “natural” lower bound, generalizing the idea of the second lowest cost. (It is easy to observe that no meaningful ratio is possible when comparing to the actual lowest cost.)

**Definition 4 ([8]).** Let  $(E, \mathcal{F})$  be a set system, and  $\mathbf{c}$  a cost vector for the elements. Let  $S$  be a cheapest feasible set with respect to the  $c_e$  (where ties are broken lexicographically). We define  $\nu(\mathbf{c})$  to be the solution to the following



optimization problem.

Minimize  $\sum_{e \in S} x_e$  subject to

- (1)  $x_e \geq c_e$  for all  $e$
- (2)  $x(S \setminus T) \leq c(T \setminus S)$  for all  $T \in \mathcal{F}$
- (3) For every  $e \in S$ , there is a  $T_e \in \mathcal{F}$  such that  $e \notin T_e$  and  $x(S \setminus T_e) = c(T_e \setminus S)$

This definition essentially captures the payments in a “cheapest Nash equilibrium” of a first-price auction, and gives a natural lower bound generalizing second-lowest cost for comparison purposes.

**Definition 5.** The frugality of a mechanism  $\mathcal{M}$  for a set system  $(E, \mathcal{F})$  is

$$\phi_{\mathcal{M}} = \sup_{\mathbf{c}} \frac{p_{\mathcal{M}}(\mathbf{c})}{\nu(\mathbf{c})},$$

i.e., the worst case, over all cost vectors  $\mathbf{c}$ , of the overpayment compared to the “first-price” payments. Here,  $p_{\mathcal{M}}(\mathbf{c})$  denotes the total payments made by  $\mathcal{M}$  when the cost vector is  $\mathbf{c}$ .

### 3. A Multiplicative Penalty Mechanism

In this section, we focus on a mechanism MP with *multiplicative penalties*, as well as lower bounds, for arbitrary “hiring a team” instances. The MP mechanism always buys a solution, and so long as each agent owns one element only, it is false-name proof.<sup>2</sup> We analyze the frugality ratio of MP for arbitrary instances, and prove that it is at most  $2^n$ , matching — up to constants — a lower bound of  $\Omega(2^n)$  for any false-name-proof mechanism.

#### 3.1. The Mechanism MP

The mechanism MP is based on exponential multiplicative penalties. It is false-name-proof for arbitrary classes of set systems closed under subdivisions, *so long as each agent only owns one element* (In other words, it guards

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<sup>2</sup>In fact, MP works even if an agent owns multiple elements, so long as all of these elements are required at the same time. In other words, if we can consider a set of elements as a virtual single element, MP is false-name-proof.

against self-division by agents). We can therefore identify elements  $e$  with agents. Since we assume that each agent owns exactly one element,  $\mathcal{A}$  is automatically determined by  $E$ , so we can focus on set systems instead of owned set systems.

After the agents submit bids  $b_e$  for elements, MP chooses the set  $S^*$  minimizing  $b(S) \cdot 2^{|S|-1}$ , among all feasible sets  $S \in \mathcal{F}$ . Each agent  $e \in S^*$  is then paid her threshold bid  $2^{|S^*-e|-|S^*|}b(S^*-e) - b(S^* \setminus \{e\})$ , where  $S^*-e$  denotes the best solution (with respect to the objective function  $b(S) \cdot 2^{|S|-1}$ ) among feasible sets  $S$  not containing  $e$ . Notice that while this selection may be NP-hard in general, it can be accomplished in polynomial time for path auctions, by using the Bellman/Ford algorithm to compute the shortest path for each number of hops, and then choosing from the at most  $n$  such shortest paths.

**Theorem 1.** *For all classes of set systems closed under subdivision, MP is false-name-proof, so long as each agent only owns one element. Furthermore, it has frugality ratio  $O(2^n)$ , where  $n = |E|$ .*

**Proof.** If an agent  $e = e_0$  self-divides into  $k + 1$  elements  $e_0, \dots, e_k$ , then either all of the  $e_i$  or none of them are included in any feasible set  $S$ . Thus, we can always think of just one threshold  $\tau_k(e)$  for the self-divided agent  $e$ : if the sum of the bids of all the new elements  $e_j$  exceeds  $\tau_k(e)$ , then  $e$  loses; otherwise, it is paid at most  $(k + 1)\tau_k(e)$ . The original threshold of agent  $e$  is  $\tau(e) = \tau_0(e)$ .

The definition of the MP mechanism implies that  $\tau_k(e) \leq 2^{-k}\tau(e)$ . If  $e$  still wins after self-division (otherwise, there clearly is no incentive to self-divide), the total payment to  $e$  is at most  $(k + 1)2^{-k}\tau(e)$ . The alternative of not self-dividing, and submitting a bid of 0, yields a payment of  $\tau(e) \geq (k + 1)2^{-k}\tau(e)$ . Thus, refraining from self-division is a dominant strategy. Given that no agent will submit false-name bids, the monotonicity of the selection rule implies that the mechanism is incentive compatible, and we can assume that  $b_e = c_e$  for all agents  $e$ .

To prove the upper bound on the frugality ratio, consider again any winning agent  $e \in S^*$ . Her threshold bid is

$$\tau(e) = \min_{T \in \mathcal{F}: e \notin T} 2^{|T|-|S^*|}c(T) - c(S^* \setminus \{e\}),$$

and the total payment is the sum of individual thresholds for  $S^*$ ,

$$\begin{aligned} p_{\text{MP}}(\mathbf{c}) &= \sum_{e \in S^*} \min_{T \in \mathcal{F}: e \notin T} 2^{|T| - |S^*|} c(T) - c(S^* \setminus \{e\}) \\ &\leq 2^{n - |S^*|} \sum_{e \in S^*} \min_{T \in \mathcal{F}: e \notin T} c(T). \end{aligned}$$

To obtain the frugality ratio from this upper bound on the payments, we need a lower bound on the value  $\nu(\mathbf{c})$  (see Definition 5). Let  $S$  be the cheapest solution with respect to the  $c_e$ , i.e., without regard to the sizes of the sets. By Definition 4,  $\nu(\mathbf{c}) = \sum_{e \in S} x_e$ , subject to the constraints of the mathematical program given. Focusing on any fixed agent  $e'$ , we let  $T_{e'}$  denote the set from the third constraint of Definition 4, and can rewrite

$$\begin{aligned} \nu(\mathbf{c}) &= \sum_{e \in S \setminus T_{e'}} x_e + \sum_{e \in S \cap T_{e'}} x_e \\ &= \sum_{e \in T_{e'} \setminus S} c_e + \sum_{e \in T_{e'} \cap S} x_e \geq c(T_{e'}). \end{aligned} \tag{1}$$

Since this inequality holds for all  $e'$ , we have proved that  $\nu(\mathbf{c}) \geq \max_{e \in S} c(T_e)$ . On the other hand, we can further bound the payments by

$$\begin{aligned} 2^{n - |S^*|} \sum_{e \in S^*} \min_{T \in \mathcal{F}: e \notin T} c(T) &\leq |S^*| \cdot 2^{n - |S^*|} \cdot \max_{e \in S^*} \min_{T \in \mathcal{F}: e \notin T} c(T) \\ &\leq \frac{|S^*|}{2^{|S^*|}} \cdot 2^n \cdot \max_{e \in S} \min_{T \in \mathcal{F}: e \notin T} c(T) \\ &\leq 2^n \cdot \max_{e \in S} c(T_e). \end{aligned}$$

Here, the middle inequality followed because for all  $e \in S^* \setminus S$ , the minimizing set  $T$  is actually equal to  $S$ , and therefore cannot have larger cost than  $c(T_e)$  for any  $e \in S$ , by definition of  $S$ . Thus, the frugality ratio of MP is

$$\phi_{\text{MP}} = \sup_{\mathbf{c}} \frac{p_{\text{MP}}(\mathbf{c})}{\nu(\mathbf{c})} \leq \frac{2^n \max_{e \in S} c(T_e)}{\max_{e \in S} c(T_e)} = 2^n.$$

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### 3.2. An Exponential Lower Bound

An exponentially large frugality ratio is not desirable. Unfortunately, any mechanism which is false-name-proof will have to incur such a penalty, as shown by the following theorem.

**Theorem 2.** *Let  $\mathcal{C}$  be any class of monopoly free set systems closed under subdivisions, and  $\mathcal{M}$  be any truthful and false-name-proof mechanism for  $\mathcal{C}$ . Then, the frugality ratio of  $\mathcal{M}$  on  $\mathcal{C}$  is  $\Omega(2^n)$  for set systems with  $|E| = n$ .*

**Proof.** Let  $(E_0, \mathcal{F}_0) \in \mathcal{C}$  be a set system minimizing  $|E_0|$ . Let  $S^* \in \mathcal{F}_0$  be the winning set under  $\mathcal{M}$  winning when all agents  $e \in E_0$  bid 0, and let  $e \in S^*$  be arbitrary, but fixed. Because  $(E_0, \mathcal{F}_0)$  is monopoly free, there must be a feasible set  $T \in \mathcal{F}_0$  with  $e \notin T$  and  $T \not\subseteq S^*$ . Among all such sets  $T$ , let  $T_e$  be one minimizing  $|S^* \cup T|$ , and let  $\hat{e}$  in  $T_e \setminus S^*$  be arbitrary. Define  $Z = (T_e \cup S^*) \setminus \{e, \hat{e}\}$  (the “zero bidders”), and  $I = E_0 \setminus (T_e \cup S^*)$  (the “infinity bidders”). Consider the following bid vector: both  $e$  and  $\hat{e}$  bid 1, all agents  $e' \in Z$  bid 0, and all agents  $e' \in I$  bid  $\infty$ . Let  $W$  be the winning set. We claim that  $W$  must contain at least one of  $e$  and  $\hat{e}$  (w.l.o.g., assume that  $e \in W$ ). For  $W$  cannot contain any of the infinity bidders. And if it contained neither  $e$  nor  $\hat{e}$ , then  $W$  would have been a candidate for  $T_e$  with smaller  $|W \cup S^*|$ , which would contradict the choice of  $T_e$ .

Now, let  $(E_k, \mathcal{F}_k)$  be the set system resulting if agent  $e$  self-divides into new agents  $e_0, \dots, e_k$ , for  $k \geq 0$ . Define  $\tau(j, k)$ , for  $j = 0, \dots, k$ , to be the threshold bid under  $\mathcal{M}$  for agent  $e_j$  in the set system  $(E_k, \mathcal{F}_k)$ , given that all  $e' \in Z$  bid 0, all  $e' \in I$  bid  $\infty$ , and all  $e_i$  for  $i \neq j$  also bid 0, while  $\hat{e}$  bids 1. Above, we thus showed that  $1 \leq \tau(0, 0) < \infty$ . We now show by induction on  $d$  that for all  $d$ , there exists an  $h \leq d$  such that

$$2^{-d} \sum_{i=0}^k \tau(i, k) \geq \sum_{i=h}^{k+h} \tau(i, k+d).$$

The base case  $d = 0$  is trivial. For the inductive step, assume that we have proved the statement for  $d$ . Because  $\mathcal{M}$  is truthful, the payment of an agent is exactly equal to the threshold bid, so each agent  $i$  is paid  $\tau(i, k+d)$  in the auction on the set system  $(E_{k+d}, \mathcal{F}_{k+d})$  with the bids as given above. If agent  $i$  were to self-divide into two new agents, the new set system would be  $(E_{k+d+1}, \mathcal{F}_{k+d+1})$ , and the payment of agent  $i$  (who is now getting paid as two pseudo-agents  $i$  and  $i+1$ ) would be  $\tau(i, k+d+1) + \tau(i+1, k+d+1)$ . Because  $\mathcal{M}$  was assumed to be false-name-proof, it is not in the agent’s best interest to self-divide in such a way, i.e.,  $\tau(i, k+d) \geq \tau(i, k+d+1) + \tau(i+1, k+d+1)$ .

Summing this inequality over all agents  $i = h, \dots, h+k$ , we obtain

$$\begin{aligned} \sum_{i=h}^{h+k} \tau(i, k+d) &\geq \sum_{i=h}^{h+k} (\tau(i, k+d+1) + \tau(i+1, k+d+1)) \\ &= \sum_{i=h}^{h+k} \tau(i, k+d+1) + \sum_{i=h+1}^{h+k+1} \tau(i, k+d+1). \end{aligned}$$

Define  $\ell = 0$  if  $\sum_{i=h}^{h+k} \tau(i, k+d+1) \leq \sum_{i=h+1}^{h+k+1} \tau(i, k+d+1)$ ; otherwise, let  $\ell = 1$ . Then, the above inequality implies that

$$\sum_{i=h}^{h+k} \tau(i, k+d) \geq 2 \sum_{i=h+\ell}^{h+k+\ell} \tau(i, k+d+1).$$

Finally, setting  $h' := h + \ell$ , we can combine this inequality with the induction hypothesis to obtain that

$$2^{-(d+1)} \sum_{i=0}^k \tau(i, k) \geq \sum_{i=h'}^{k+h'} \tau(i, k+d+1),$$

which completes the inductive proof.

Applying this equation with  $k = 0$ , we obtain that for each  $d \geq 0$ , there exists an  $h \leq d$  such that  $\tau(h, d) \leq 2^{-d} \cdot \tau(0, 0)$ . Thus, in the set system  $(E_d, \mathcal{F}_d)$ , if all infinity bidders have cost  $\infty$ , agent  $e_h$  has cost just above  $2^{-d}\tau(0, 0)$ , and all other agents have cost 0, then agent  $\hat{e}$  must be in the winning set, and must be paid at least 1. But it is easy to see that in this case,  $\nu(c) = 2^{-d}\tau(0, 0)$ , and the frugality ratio is thus at least  $2^d/\tau(0, 0) = \Omega(2^d)$  (since  $\tau(0, 0)$  is a constant independent of  $d$ ). Finally,  $|E_d| = |Z| + |I| + d + 2$ , and because  $Z$  and  $I$  are constant for our class of examples, the frugality ratio is  $2^{-(|Z|+|I|+2)} \cdot 2^n/\tau(0, 0) = \Omega(2^n)$ .  $\blacksquare$

In this section, we presented the MP mechanism based on multiplicative penalties. MP always buys a feasible set. However, MP is guaranteed to be false-name-proof only when each agent owns a single element. At this point, we do not know if there exist any false-name-proof mechanisms against identifier splitting which *always* buy a set at finite cost. This is an intriguing open question for future work.

#### 4. An Additive Penalty Mechanism with Reserve Cost

We next propose another false-name-proof mechanism AP based on additive penalties and a reserve cost. The mechanism requires no assumption on whether agents have single or multiple elements in a set system, and we will prove that it is false-name-proof even when agents own multiple elements. However, AP does not always purchase a feasible set; it requires the auctioneer to decide on a *reserve cost*, and will only purchase a solution if there is a feasible solution whose cost (including penalties) does not exceed the reserve cost.

We can interpret the reserve cost as an upper bound on the cost (including penalties) the auctioneer is willing to pay. This is particularly reasonable if we assume that the auctioneer already has a way of performing the task using a single agent of cost  $r$ , such as a direct edge  $(s, t)$  with cost  $r$  in a network. If the bids by agents are such that the auctioneer chooses this alternative, then none of the agents (including the auctioneer) receives positive utility. Clearly, the right choice of the reserve cost  $r$  will be crucial for the performance of the mechanism.

##### 4.1. The AP mechanism

The AP mechanism is based on adding to the reported costs of the agents a penalty growing in the number of agents participating in a solution. For any set  $S \in \mathcal{F}$ , let  $w(S)$  denote the number of (pseudo-)agents owning one or more elements of  $S$ , called the *width* of the set  $S$ . The width-based *penalty* for a set  $S$  of width  $w(S)$  is  $D_r(w(S)) = (1 - 2^{1-w(S)}) \cdot r$ . Based on the reported costs and the penalty, we define the *adjusted cost* of a set  $S$  to be  $\beta(S) = b(S) + D_r(w(S))$ .

The AP mechanism first determines the set  $S^*$  minimizing the adjusted cost  $\beta(S)$ , among all feasible sets  $S \in \mathcal{F}$ . If its adjusted cost exceeds the reserve cost  $r$ , then AP does not purchase any set, and does not pay any agents. Otherwise, it chooses  $S^*$ , and pays each winning agent (i.e., each agent  $i$  with  $S^* \cap A^i \neq \emptyset$ ) her threshold bid

$$p_i = \min(r, \beta(S^{-i})) - (b(S^* \setminus A^i) + D_r(w(S^*)))$$

with respect to  $\beta(S)$ . Here,  $S^{-i}$  denotes the best solution with respect to  $\beta(S)$  such that  $S^{-i}$  contains no elements from  $A^i$ .

Notice that if we assume that the auctioneer requires an additional cost of  $(1 - 2^{1-w(S)}) \cdot r$  for handling a team  $S$ , then AP is identical to the VCG

mechanism with reserve cost  $r$ , since the adjusted cost becomes the true total cost (including the additional cost of the auctioneer). Thus, if we assume that there exists no false-name manipulation, it is natural that AP is incentive compatible since it is one instance of VCG.

**Example 1.** Consider the example in Figure 1. Assume that the reserve cost is  $r = 10$ . If agent  $X$  does not split identifiers, the adjusted cost of the path  $s-v-t$  is 2 (since it only involves one agent, the penalty is 0), and the adjusted cost of the edge  $s-t$  is 8. Thus, the payment to agent  $X$  is 8.

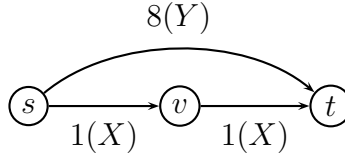


Figure 1: An example of AP.

If agent  $X$  instead uses two different identifiers  $X'$  and  $X''$  for the two edges, the penalty for the path  $s-v-t$  is  $10/2 = 5$ . Thus, while the path still wins, the payment to each of  $X'$  and  $X''$  is now  $8 - (1 + 5) = 2$ , so the total payment to agent  $X$  via pseudo-agents is 4. In particular, agent  $X$  has no incentive to split identifiers in this case.

#### 4.2. Analysis of AP

In this section, we prove that simply submitting the pair  $(b_e, i)$  for each element  $e \in A^i$  is a dominant strategy for each agent  $i$  under the mechanism AP. Furthermore, we prove that the payments of the AP mechanism never exceed  $r$ . As a first step, we prove that it never increases an agent's profit to engage in identifier splitting.

**Lemma 1.** Suppose that agent  $i$  owns elements  $A^i$ , and splits identifiers into  $i', i''$ , with sets  $A^{i'}, A^{i''}$ , such that  $A^{i'} \cup A^{i''} = A^i$ . Then, the profit agent  $i$  obtains after splitting is no larger than that obtained before splitting.

**Proof.** Let  $S^* \in \mathcal{F}$  be the winning set prior to agent  $i$ 's identifier split. We first consider the case when the winning set does not change due to the identifier split. If only one of the new pseudo-agents  $i', i''$  wins (say,  $i'$ ), then  $\beta(S^{-i'}) \leq \beta(S^{-i})$ , because every feasible set not using elements from  $A^i$  also

does not use elements from  $A^{i'}$ . Hence, the payment of  $i$  could only decrease, and we may henceforth assume that both  $i'$  and  $i''$  win, which means that the width of the winning set  $S^*$  increases from  $w(S^*)$  to  $w(S^*) + 1$ .

For simplicity, we write  $B^{-i} = \min(r, \beta(S^{-i}))$ , and similarly for  $i'$  and  $i''$ . The payment to  $i$  before the split is  $B^{-i} - (b(S^* \setminus A^i) + D_r(w))$ , whereas the new payment after the split is

$$\begin{aligned} & B^{-i'} - (b(S^* \setminus A^{i'}) + D_r(w+1)) + B^{-i''} - (b(S^* \setminus A^{i''}) + D_r(w+1)) \\ &= B^{-i'} + B^{-i''} - 2b(S^*) + b(S^* \cap A^i) - 2D_r(w+1). \end{aligned}$$

As argued above, we have that  $B^{-i''} \leq B^{-i}$ , and by definition of  $B^{-i'}$ , we also know that  $B^{-i'} \leq r$ . Thus, canceling out penalty terms, the increase in payment to agent  $i$  is bounded from above by

$$\begin{aligned} B^{-i'} + B^{-i''} - B^{-i} - b(S^*) - r &\leq r + B^{-i} - B^{-i} - b(S^*) - r \\ &= -b(S^*) \\ &\leq 0. \end{aligned}$$

Hence, identifier splitting can only lower the payment of agent  $i$ . Since the total cost incurred by agent  $i$  stays the same, this proves that there is no benefit in identifier splitting.

Next, suppose that the winning set after the split changes to  $S'^* \neq S^*$ . Clearly, if  $i$  does not win at all after the split, i.e.,  $S'^* \cap A^i = \emptyset$ , then  $i$  has no incentive to split identifiers. Otherwise, if  $i$  does win after the split, then  $i$  must also win before the split. For the split can only increase  $D_r(w(S))$  for all sets  $S$  containing any of  $i$ 's elements, while not affecting  $D_r(w(S))$  for other sets. We can assume w.l.o.g. that agent  $i$  bids  $\infty$  on all elements  $e \in A^i \setminus S'^*$ . For the winning set will stay the same, because  $\beta(S'^*)$  stays the same, and  $\beta(S)$  can only increase for other sets  $S$ , and the payments can only increase.

But then,  $S'^*$  will also be the winning set if  $i$  does not split identifiers (the adjusted cost  $\beta(S'^*)$  decreases, while all other adjusted costs stay the same). Now, we can apply the argument from above to show that the payments to agent  $i$  do not increase as a result of splitting identifiers. Thus, so long as an agent can submit bids of false cost instead, it is never a dominant strategy to split identifiers.  $\blacksquare$

Lemma 1 can be extended naturally to deal with  $k$ -way identifier splitting. Notice that the proof also shows that AP is false-name-proof against self-division.



**Theorem 3.** *For all classes of set systems closed under subdivision, AP is false-name-proof, even if agents can own multiple elements and split identifiers. Thus, for each agent  $i$ , submitting bids  $(c_e, i)$  for each element  $e \in A^i$  is a dominant strategy.*

**Proof.** First, notice that if an agent owns two elements in the winning solution, AP does not treat the agent differently from if she only owned one element. Thus, the proof of Lemma 1 also shows that self-division can never be beneficial for an agent, and we can assume from now on that no agent will self-divide or split identifiers. Thus, each agent  $i$  submits bids  $(b_e, i)$  for all elements  $e \in A^i$ . If the set  $S^* \in \mathcal{F}$  wins under AP, agent  $i$ 's utility is

$$p_i - c(S^* \cap A^i) = B^{-i} - (b(S^* \setminus A^i) + D_r(w(S^*)) + c(S^* \cap A^i)).$$

Since  $B^{-i}$  is a constant independent of the bids  $b_e$  by agent  $i$ , agent  $i$ 's utility is maximized when  $(b(S^* \setminus A^i) + D_r(w(S^*)) + c(S^* \cap A^i))$  is minimized. But this is exactly the quantity that AP will minimize when agent  $i$  submits truthful bids for all her elements; hence, truthfulness is a dominant strategy. ■

The next theorem proves that an auctioneer with a reserve cost of  $r$  faces no loss.

**Theorem 4.** *The sum of the payments made by AP to agents never exceeds  $r$ .*

**Proof.** Because we already proved that AP is false-name-proof, we can without loss of generality identify  $c_e$  and  $b_e$  for each element  $e$ . When  $w$  agents are part of the winning set  $S^*$ , the payment to agent  $i$  is

$$\begin{aligned} p_i &= B^{-i} - (c(S^* \setminus A^i) + D_r(w)) \\ &\leq r - (c(S^* \setminus A^i) + r - \frac{r}{2^{w-1}}) \\ &\leq \frac{r}{2^{w-1}}. \end{aligned}$$

Thus, the sum of all payments to agents  $i$  is at most  $w \cdot \frac{r}{2^{w-1}} \leq r$ . ■

Since the reserve cost mechanism does not always purchase a feasible set, we cannot analyze its frugality ratio in the sense of Definition 5. (The

definition is based on the assumption that the mechanism always purchases a set.) Nevertheless, if the auctioneer already has a way of performing the task using a single agent of cost  $r$ , (such as a direct edge with higher cost in a network), we can derive bounds on the frugality ratio of the AP mechanism. These bounds cannot be taken as actual hard guarantees, since we need to assume that the auctioneer was “lucky” in choosing the right reserve cost.

Specifically, assume that the auctioneer chose a reserve cost  $r \leq 2^n \cdot \max_{e \in S} c(T_e)$ , where  $S$  is the cheapest solution, and the sets  $T_e$  are defined by the third constraint of Definition 4. Since the total payment of AP does not exceed  $r$  by Theorem 4, and  $\nu(\mathbf{c}) \geq \max_{e \in S} c(T_e)$  by Inequality 1, we obtain an upper bound of  $O(2^n)$  on the frugality ratio, matching that of MP. More generally, if the auctioneer chooses an  $r \leq f(n) \cdot \max_{e \in S} c(T_e)$ , then the frugality ratio of the mechanism is  $O(f(n))$ .

### 4.3. Experiments

We complement the analysis of the previous section with experiments for shortest  $s$ - $t$  path auctions on random graphs. Our simulation compares the payments of AP with VCG, under the assumption that there is in fact no false-name manipulation and each agent owns one edge. Thus, we evaluate the overpayment caused by preventing false-name manipulation.

Since some of our graphs have monopolies, we modify VCG by introducing a reserve cost  $r$ . Thus, if  $S^*$  is the cheapest solution with respect to the cost, the reserve-cost VCG mechanism (RVCG) only purchases a path when  $c(S^*) \leq r$ . In that case, the payment to each edge  $e \in S^*$  is  $p_e = \min(r, c(S^{-e})) - c(S^* \setminus \{e\})$ , where  $S^{-e}$  is the cheapest solution not containing  $e$ .

Our generation process for random graphs is as follows: 40 nodes are placed independently and uniformly at random in the unit square  $[0, 1]^2$ . Then, 200 independent and uniformly random node pairs are connected with edges.<sup>3</sup> The cost of each edge  $e$  is its Euclidean length. We evaluate 100 random trials; in each, we seek to buy a path between two randomly chosen nodes. While the number of nodes is rather small compared to the real-world networks on which one would like to run auctions, it is dictated by

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<sup>3</sup>We also ran simulations on random small-world networks [32]. Our results for small-world networks are qualitatively similar, and we therefore focus on the case of uniformly random networks here.

the computational complexity of the mechanisms we study. Larger-scale experiments are a fruitful direction for future work.

Figure 2 shows the average social surplus (the difference between the reserve cost and the true cost incurred by edges on the chosen path,  $r - \sum_{e \in S^*} c_e$ ) in AP and RVCG, as well as the ratio between the two, when varying the reserve cost  $r \in [0, 3.5]$ . The social surplus for both increases roughly linearly under both mechanisms. While the plot shows some efficiency loss by using AP, the efficiency is always within a factor of about 60% for our instances, and on average around 80%.

Figure 3 illustrates the average payments of the auctioneer. Clearly, small reserve costs lead to small payments, and when the reserve costs are less than 1.8, the payment of AP is in fact smaller than that of RVCG. As the reserve cost  $r$  increases, RVCG's payments converge, while those of AP keep increasing almost linearly. The reason is that the winning path in AP tends to have fewer edges than other competing paths, and is thus paid an increased bonus as  $r$  increases. We would expect such behavior to subside as there are more competing paths with the same number of edges.

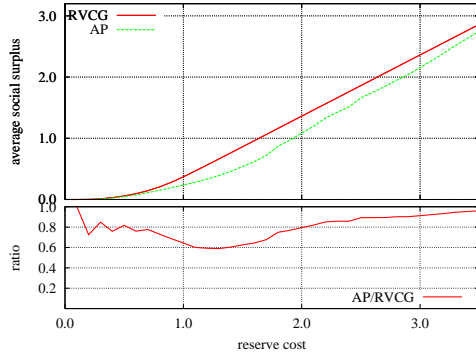


Figure 2: Social surplus.

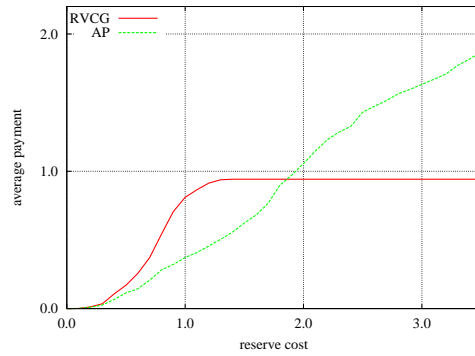


Figure 3: Payments.

## 5. Concluding remarks

In this paper, we initiated the investigation of false-name-proof mechanisms for hiring a team of agents. In this model, the structure of the set system may not be completely known to the auctioneer. We first presented a mechanism MP based on exponential multiplicative penalties, which always buys a solution, but is false-name-proof only when each agent has exactly

one element. We proved that MP has a frugality ratio of  $2^n$ . This is within a constant factor of optimal for all classes of set systems, as we also proved a lower bound of  $\Omega(2^n)$  for all false-name-proof mechanisms.

We also presented an alternative mechanism AP with exponential additive penalties and a reserve cost, which is false-name-proof even when each agent has multiple elements. We evaluated AP experimentally; while it has smaller social surplus compared to VCG, the difference is bounded by small multiplicative constants in all of our experiments. The payments of AP are smaller than those of the VCG mechanism when the reserve cost is small. Although the payments increase linearly in the reserve cost, they never exceed the reserve cost.

It remains open whether there is a mechanism which always purchases a solution, and is false-name-proof even when each agent has multiple elements. This holds even for such seemingly simple cases as  $s$ - $t$  path auctions. It may be possible that no such mechanism exists, which would be an interesting result in its own right. The difficulty of designing false-name-proof mechanisms for hiring a team is mainly due to a lack of useful characterization results for incentive-compatible mechanisms when agents have multiple parameters. While a characterization of truthful mechanisms has been given by Rochet [33], this condition is difficult to apply in practice.

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